Renewable and Sustainable Energy Reviews 39 (2014) 883–890

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

An economic analysis of a stand-alone and grid-connected cattle farm

R. Velo *, L. Osorio, M.D. Fernández, M.R. Rodríguez

Agroforestry Engineering Department, Escuela Politécnica Superior, Campus Universitario, University of Santiago de Compostela, Lugo 27002, Spain

ARTICLE INFO

Article history:
Received 12 February 2014
Received in revised form
27 May 2014
Accepted 19 July 2014
Available online 8 August 2014

Keywords:
Off-grid
Stand-alone system
Hybrid system

ABSTRACT

This paper presents an economic study of electricity supply to a dairy cattle farm of 50 livestock units. We compared a stand-alone battery-wind-diesel hybrid system with an only-grid connected system and we analyzed four locations in Spain with different average wind speeds. The farm's electricity demand is 63 kWh/d and the hybrid system designed for its supply is made up of a 20 kW wind turbine, a diesel generator and a battery. All simulations were made with the HOMER© (Hybrid Optimization Model for Electric Renewables) software. Through a sensitivity analysis we can determine the economic viability of different options and sizes of the components of the installation.

In locations with an average wind speed higher than 7.39 m/s, a stand-alone system is profitable as long as the distance to the grid is higher than 7 km, the price of electricity is 0.192 €/kWh and diesel price is 1.8 €/L. If 800 Ah-battery is used instead of 200 Ah, the COE will be reduced by 18% in location with 7.39 m/s average wind speed.

Contents

1. Introduction

The EU is committed to reducing emissions of greenhouse gases by up to 80–95% below 1990 levels by 2050 while ensuring energy supply and competitiveness. These objectives imply a permanent development of all renewable energy sources and especially wind power. Currently is the leading technology in electricity generation and will provide in 2050 from 32% to 49% of total electricity consumption [1].

The International Energy Agency appeals to governments to encourage actions that accurately reflect the real cost of energy production and consumption. The low carbon electricity should be the core of any sustainable energy system since it can produce drastic reductions in carbon dioxide emissions in industry, transport and services sector [2]. Since the cost of wind energy is still higher than the market price of electricity from conventional energy sources, many countries (Denmark, Germany, Spain, etc.) have introduced feed-in-tariffs that use them as a very important instrument to develop electricity from renewable sources.

There is an increase in the market of small wind turbines for off-grid installations that make decentralized electricity generation a competitive solution. Hybrid systems have a huge potential to substitute fossil fuels in the current energy systems and will cause a considerable reduction in the cost of infrastructures [3].

In recent years, wind turbine technologies have advanced considerably in power control systems and in wind field modeling as important part of a structural analysis of wind turbines. There are still obstacles to the diffusion of stand-alone and small grid-connected systems, such as unfavorable regulations and price settings that lead to the undervaluing of grid-connected systems.

Lundsager et al. [4], based on previous experiences, emphasize various general recommendations for the installation of isolated

* Corresponding author. Tel.: +34 982 823 256; fax +34 982 285 926.
E-mail address: ramon.velo@usc.es (R. Velo).

http://dx.doi.org/10.1016/j.rser.2014.07.156
1364-0321/

wind energy projects and between us we emphasize that these projects should be part of a concerted plan of action within a national program. Also we underline that it is desirable to avoid further difficulties, study in detail the feasibility of the project.

There are several tools to design hybrid systems as Hybrid Optimization Model for Electric Renewable (HOMER), Hybrid2 software package (HYBRID2), Hybrid Optimization by Genetic Algorithms (HOGA) and Transient Energy System Simulation program (TRNSYS). The ideal tool is highly dependent on the specific objectives that must be fulfilled, of the applications, and combined with other factors such as the energy-sectors considered, technologies accounted for, time parameters used, tool availability, and previous studies [5].

One of the reasons for the high costs of electricity supply can be attributed to the dependence on centralized energy systems and operating mainly fossil fuels and also require large investments for setting transmission and distribution networks to reach remote regions [6]. The stand-alone systems have disadvantages like excess battery costs, low capacity factor and finite capacity to store electricity forcing to throw away the extra energy generated [7]. Economic feasibility and load factors, besides the environmental factors, help decide between a grid-connected system in front of other stand-alone system. Therefore, it is critical to examine the conditions under which both systems are profitable.

Hybrid solar or wind energy systems are an alternative to energy supply by electricity network. Several procedures have been used to optimize the size of their components [8–17]. Taking into account the duration of the batteries, diesel generators and fuel price uncertainty, for sizing of a wind–diesel hybrid system, it was concluded that the optimal solution is close to many sub-optimal solutions characterized with good economic costs but also depends on the operating conditions of the system adopted [18].

Stand-alone electric generation hybrid systems are more appropriate than those that only have one power source for off-grid supply, but the design, control and optimization of hybrid systems are usually very complex [19]. Celik [20] states that the choice of scenarios based on the worst months can lead to a less optimal choice of solar–wind hybrid system in terms techno-economic. While providing a high level of autonomy, the system cost is too high and the same level of autonomy could be obtained at less cost by introducing a third power supply.

Kaldellis et al. [21] develop an algorithm for the estimation of the maximum wind energy that can be absorbed by an autonomous system from the knowledge of the restrictions of an autonomous electricity network.

The importance of storage on the economics of hybrid wind-diesel power systems in Saudi Arabia is assessed. The percentage fuel savings by using hybrid 100 kW system is 27% as compared to diesel-only situation [22]. Dalton et al. [23] compared the technical and economic feasibility of various renewable energy hybrid systems compared to the option of supplying electric power to the network in a hotel in Australia and shows that are competitive in certain cases studied. Stand-alone systems with renewable energy sources require their oversizing and to fulfill significant energy storage requirements, which will cause relatively high costs. Kaldellis et al. [24] propose an integrated technical–economical methodology for the evaluation of wind and photovoltaic stand-alone power systems.

Lujano-Rojas et al. [25] use a strategy for charge control to minimize the energy supplied by the diesel generator and the battery and to optimize the use of renewable energy, subjected to restrictions imposed by user behavior and the charges work cycle. Notton et al. [26] developed a methodology that allows determining the optimal configuration of an isolated system according to the percentage of the connected load and taking into account physical and economic cost considerations. Elhadidy and Shaahid [27] study the impact caused by the installation of a battery in a wind–solar hybrid system.

The small diesel generators, up to 100 kW, are only 25–35% of efficient, because the fuel costs in remote off-grid communities are higher [28]. In Canada are identified 89 villages with at least 5 m/s that could be considered as candidates for remote wind power. Without any incentive, a maximum of 10 villages are possible candidates for wind–diesel projects economically viable and an incentive rate of 0.15 $/kWh extend this number to 62 potential candidates for such project [29].

This paper is structured as follows. Section 2 presents the data analysis and the methodology used, Section 3 presents the results and conclusions are included in Section 4.

2. Material and methods

We analyzed four possible locations for a dairy cattle farm with 50 livestock units with electricity supplied by a small wind turbine. The criteria for the choice were the annual average wind speed and the operation hours of the small wind turbine. Both parameters were different for each location. Some specifications for the locations are shown in Table 1. The main advantage of analyzing the four locations is the possibility of importing the results to other locations with similar characteristics.

We used a 20 kW Westwind turbine. Table 2 shows some specifications of the chosen model and Fig. 1 represents its power curve. It is worth noting that the turbine starts at 4.5 m/s and is efficient in situations of low speeds, since many dairy cattle farms are not located in the most suitable locations. The price of the wind turbine includes the price of the turbine and the tower, as well as the cost of the installation, which is estimated at 30% of the wind turbine's cost. The price of replacement of the components of the hybrid system is estimated at 75% of the initial cost and the operation and maintenance cost is estimated at 3% [30].

According to all of the above, we simulated the system with HOMER software tool, developed by the National Renewable Energy Laboratory (NREL) [31]. HOMER is a global standard for economic analysis of sustainable remote micro-grid systems and creates a computer-generated system as close to reality as possible by considering the effect of the variation of the values with the time of electric charge and wind speed.

The criteria of evaluation used are the net present cost (NPC), the cost of energy (COE) and the renewable fraction (RF) percentage. NPC of the system is the total cost of installing and operating the system over its lifetime, with future cash flows discounted to the present. The NPC includes the costs of the initial construction, the component replacements, maintenance and fuel for the project lifetime of 25 years. HOMER uses the following equation to calculate the total NPC. The NPC estimation in HOMER also takes into account salvage costs, which is the residual value of the power system components at the end of the project lifetime.

$$\mathrm{NPC} = \frac{C_{ann,\,tot}}{\mathrm{CRF}(i, R_{proj})} \quad (€) \tag{1}$$

where, $C_{ann,tot}$ is the total annualized cost [€/yr], *CRF* is the capital recovery factor, and R_{proj} is the project lifetime [yr].

The capital recovery factor (CRF) is a ratio used to calculate the present value of an annuity (a series of equal annual cash flows):

$$\mathrm{CRF}(i, n) = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{2}$$

where i is the annual real interest rate (4%) [32] and n is the number of years (25).

HOMER assumes that all prices escalate at the same rate and this method allows inflation to be factored out of the analysis The

Table 1
Characteristics of studied locations.

Location	Madrid	Burgos	Alto do Rodicio	Punta Candelaria
Coordinates	40°22′40″N 3°47′21″W	42°21′22″N 3°37′57″W	42°17′60″N 7°35′24″W	43°42′36″N 8°3′0″W
Average annual wind speed (m/s)	3.92	5.08	6.19	7.39
Weibull *K* factor	1.42	1.68	1.40	1.60
Turbine's operation hours (h/yr)	4111	5557	7431	6523

Table 2
Specifications of a 20 kW Westwind wind turbine.

Description	Westwind 20 kW
Rated wind speed (m/s)	14
Power at rated wind speed (kW)	20
Cut-in wind speed (m/s)	4.0
Maximum power output (kW)	22.74
Number of blades	3
Blade diameter (m)	10.4
Blade sweep area (m^2)	81.67
Control system	Automatic side furling
Gearbox	None
Brakes	Electro-dynamic
Generator	Permanent magnet alternator
Yaw control	Tail vane
Tower height (m)	18
Capital cost (€)	67,942
Replacement cost (€)	50,957
Operation and maintenance cost (€/yr)	2038
Lifetime (years)	25

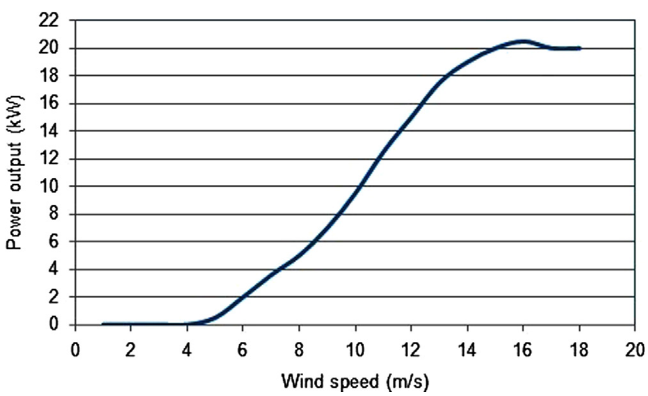

Fig. 1. Westwind 20 kW power curve.

annual real interest rate is equal to the nominal interest rate minus the inflation rate. HOMER converted the capital cost of each component to an annualized cost by amortizing it over its component lifetime using the real discount rate.

The COE is the average cost per kWh of useful electrical energy produced by the system. To calculate the COE, it divides the annualized cost of producing electricity by the total useful electrical energy production:

$$COE = \frac{C_{ann,\ tot}}{E_{prim,\ AC} + E_{prim,\ DC} + E_{def}} \quad (€/kWh) \tag{3}$$

where, $C_{ann,tot}$ is the total annualized cost of the system [€/yr], $E_{prim,AC}$ is the AC primary load served [kWh/yr], $E_{prim,DC}$ is the DC primary load served [kWh/yr], and E_{def} is the deferrable load served [kWh/yr].

Renewable fraction (RF) is the portion of the system's total energy production originating from renewable power sources and it is calculated by dividing the total renewable power production (E_{ren}) by the total energy production (E_{tot}).

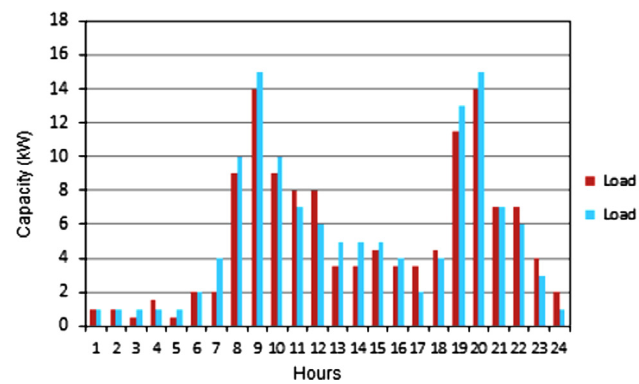

Fig. 2. Profiles of daily electricity demand.

$$RF = \frac{E_{ren}}{E_{tot}} \tag{4}$$

Ideally, the priority of battery charging should take into account future load and supply and under the load following strategy, a generator produces only enough power to serve the load, which does not charge the battery bank. Under the cycle charging strategy, whenever a generator operates it runs at its maximum rated capacity, charging the battery bank with any excess electricity produced. The generator will not stop charging the battery bank until it reaches the specified state of charge set by the user. Cycle charging was chosen as the case study dispatch strategy as it is the more suitable for large-scale systems, providing greater longevity both for the diesel generator and battery bank, due to less frequent stopping and starting, and battery bank and a reduced risk of over-discharge. HOMER's operating reserve constraint is the additional reserve capacity which a system requires to account for sudden increases in the electric load or sudden decreases in the renewable power output. An hourly electrical load reserve of 10% was defined for the present case study [22].

We compare two potential options for power supply to the farm: on the one hand, a grid connected system and on the other hand, a stand-alone hybrid system consisting of the above mentioned turbine and a diesel generator and a battery to stores excess energy generated. Both cover the electrical needs in the absence of wind.

Each livestock unit is supposed to produce an average of 7500 L of milk or 7650 kg/yr, which amounts to 382,500 kg/yr. If we consider an average electricity consumption of 0.06 kWh/kg of milk [33], the annual electricity demand is 22,950 kWh/yr.

Two electrical demands are considered according to the period of the year, with a different distribution during the day. Load 1 to the period between October and March (average: 64.2 kWh/d) and load 2 from April to September (average: 65.2 kWh/d). This different electricity demand is due to temperature differences and official time change (Fig. 2). The maximum values are dependent upon the hours that made the two milkings (08:00 and 19:00) and will cause increased demand for cooling milk [34–36].

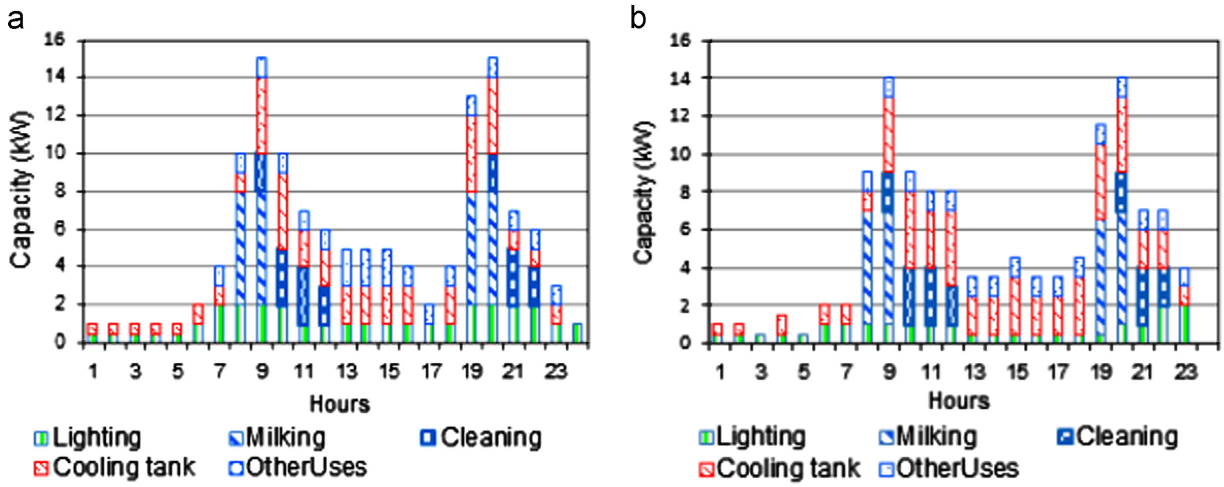

Fig. 3. Distribution of daily electricity demand. (a) Load 1 (October–March). (b) Load 2 (April–September).

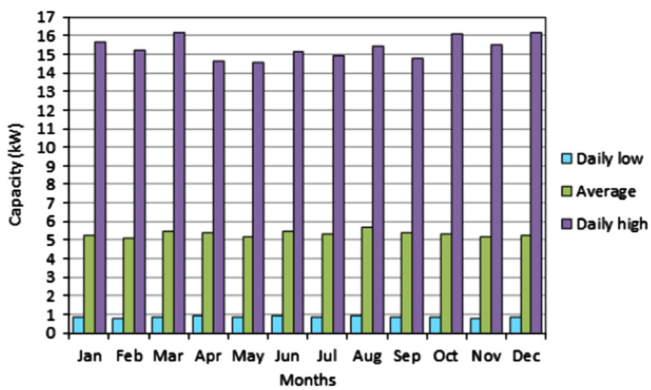

Fig. 4. Profiles of month electricity demand.

In the milking parlor are placed vacuum pump to extract milk from the cow udders (5.5 kW) and milk pump (0.5 kW) for transport to the cooling tank (4 kW) where it is cooled to 3–5 °C. It is needed for cleaning, a water pump to the milk circuits (1.5 kW), a scraper for extracting manure from the stables (2.0 kW) and an electric heater for water (2.0 kW). Lighting with fluorescent lamps reaches a total installed power of 5 kW. Ventilation by fans (1 kW) and other lines with various uses (1.5 kW) complete electrical needs [37,38]. So the total AC installed capacity reaches 23 kW. In Fig. 3 the distribution of consumption is observed for the two types of power demand.

HOMER simulates the work of the system by making energy balances for each of the 8760 h a year. The hourly load profile of power demand of the charges connected to the system is not available for the whole year, so it synthesizes the load profile considering the power demand of a random day and applying some random values: 15% for day-to-day randomness and 10% for time-step-to-time-step randomness. Therefore the load for each of the months will have a minimum, maximum and average value (Fig. 4). HOMER randomly draws the daily perturbation value once per day from a normal distribution with a mean of zero and a standard deviation equal to the “daily variability” input value. It randomly draws the time step perturbation value every time step from a normal distribution with a mean of zero and a standard deviation equal to the “time-step-to-time-step variability” input value.

The service charge that must be paid even if you do not use the electricity at all, it accounts for the availability of the service. In this study, the service charge is considered 643.5 €/yr in each simulation [39].

Fig. 5 shows the two diagrams of systems, stand-alone and connected to the grid with its energy flows.

In the case of a grid connected system, a sensitivity analysis was carried out to examine the effect of electricity price variation on the COE. The base electricity price is 0.160 €/kWh and the variation of 20% in the price were also studied (0.128 and 0.192 €/kWh). The distance to the electricity line was also considered (1, 3, 5, 7 and 9 km), which is an additional cost for the farm and for this option. This cost is considered as a system fixed capital cost because it occurs at the start of the project regardless of the size or architecture of the power system and it is shown in Table 3.

When electricity reaches the farm and it is distributed by the hybrid system, diesel price variations are very important, so a new sensitivity analysis was carried out to examine the effect of diesel price consumed by the generator. The base diesel price is 1.5 €/L and a variation of 20% in the price were also studied (1.2 and 1.8 €/L). We also studied the influence of the turbine's price in the COE with an increase of 25%. The excess of electricity supplied by the wind turbine is stored in a battery. In case of an energy deficit, the battery and the diesel generator will supply the energy needed. The specifications of the batteries and the generator are shown in Tables 4 and 5. The bi-directional converter (inverter/rectifier and transformer) that connects the battery to the electrical loads and to wind turbine has a capacity of 15 kW and a cost of 5899€ [41]. In this system, power cannot come from both the generator and the batteries at the same time.

The analysis of the effect of an increase in the capacity of the battery is very relevant. In order to do so, we took the base case of the study for the hybrid system. The price of diesel is 1.5 €/L and the battery is a Hoppecke 4 OPzS 200 model. We also carried out an analysis of the influence of reducing the turbine's service life from 25 to 15 years.

We also examined the hypothetical case of a 20% funding for the turbine and its replacement. The wind turbine is the most expensive element, so this price reduction could be relevant for the reduction of the total COE of the installation.

Table 6 shows all the variations analyzed in the sensitivity analysis.

3. Results

The cost effectiveness of a system configuration is determined on the basis of its NPC, so the NPC is HOMER's main economic output. Fig. 6 shows the NPC of grid-connected systems, considering different distances to the electric line and electricity's prices.

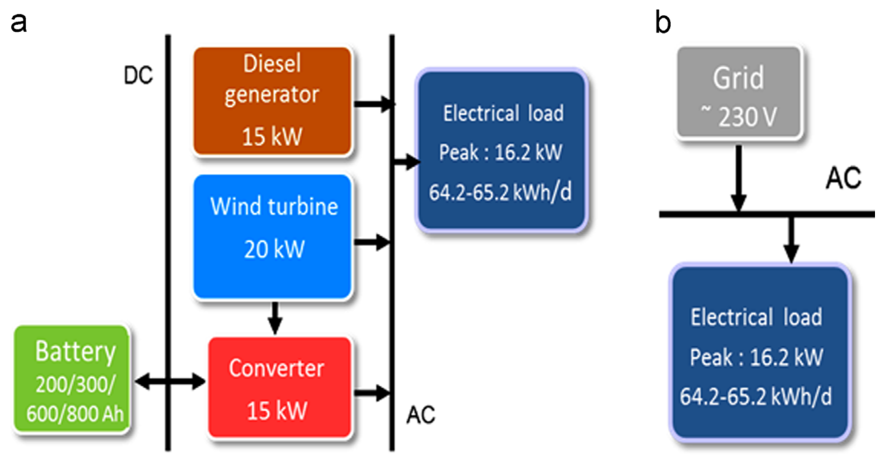

Fig. 5. Schematic diagrams of the proposed systems. (a) Stand-alone. (b) Connected to grid.

Table 3
Fixed costs in the grid connection system [40].

Distance to the electricity line (km)	Cost (€)
1	38,000
3	102,000
5	166,000
7	230,000
9	294,000

Table 6
Sensitivity analysis of the economic study.

Variables	Base case	New values		
Diesel price (€/L)	1.5	1.2	1.8	
Battery size (Ah)	200	300	600	800
Turbine price (€)	67,942	Increase of 25%	Reduction of 25%	
Lifespan (years)	25	15		
Power price (€/kWh)	0.128	0.150	0.192	

Table 4
Specification of batteries used in the study [42].

Battery type	Hoppecke 4 OPzS 200	Hoppecke 6 OPzS 300	Hoppecke 6 OPzS 600	Hoppecke 8 OPzS 800
Nominal capacity (Ah)	200	300	600	800
Nominal voltage (V)	2	2	2	2
Strings	1	1	1	1
Min. state of charge (%)	30	30	30	30
Batteries per string	60	60	60	60
Capital cost (€)	150	200	275	325
Replacement cost (€)	113	150	206	244
Operation and maintenance cost (€/yr)	4.5	6	8.25	9.75

Table 5
Characteristics of the diesel generator [43].

Generator type	Taigüer
Size (kW)	15
Voltage (V)	230
Full load fuel consumption (L/h/kW ouput))	0.25
Operating hours (h)	15,000
Capital cost (€)	4650
Replacement cost (€)	4418
Operation and maintenance cost (€/h)	0.02

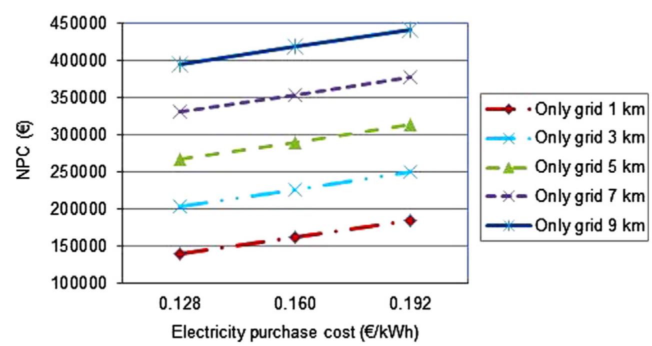

Fig. 6. Variation of net present cost (NPC) (€) in grid-connected systems.

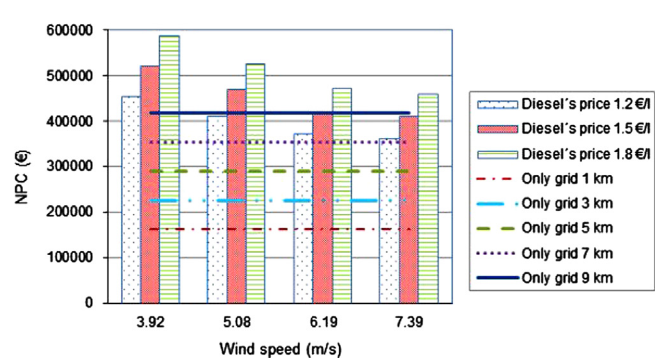

Fig. 7. Variation of net present cost (NPC) (€) comparing a stand-alone system when the electricity purchase cost is 0.16 €/kWh with grid-connected systems in the studied locations.

It can be observed that the lowest NPC for electricity supply over 25 years is 139651€ at a purchase cost from local supplier of electricity of 0.128 €/kWh, when the distance to the electricity grid is the lowest too. The cost of the grid-connected and the stand-alone systems are compared in Fig. 7. There are five continuous lines that represent the system supplied only by the electricity grid with an electricity price of 0.16 €/kWh and different distances to the electricity grid. The NPC of the hybrid system is represented by bars in each location, considering different diesel prices (base price of 1.5 €/L and its variation of 20%).

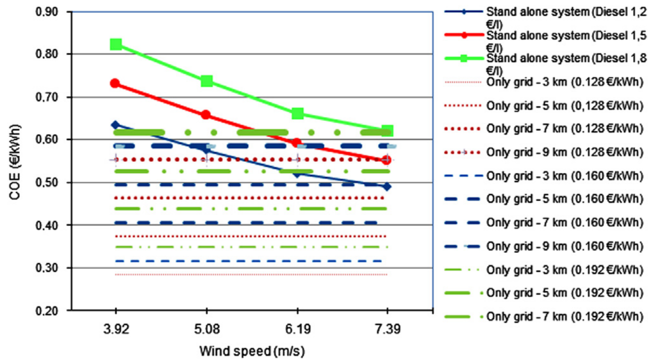

Fig. 8. Variation of cost of energy (COE) (€/kWh) comparing a stand-alone system with a grid-connected system in the studied locations.

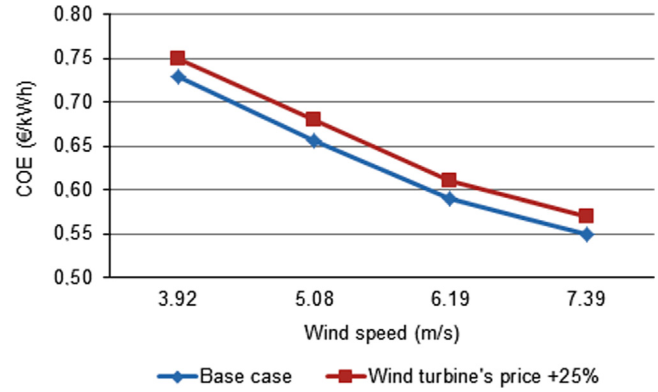

Fig. 9. Variation of cost of energy (COE) (€/kWh) comparing the base case with an increase in the initial price of the wind turbine studied in each location.

Table 7
Values of cost of energy (€/kWh) and renewable fraction (RF) for different diesel prices in the locations studied.

Wind speed (m/s)	COE			RF (%)
	Diesel: 1.2 €/L	Diesel: 1.5 €/L	Diesel: 1.8 €/L	
3.92	0.63	0.73	0.82	22
5.08	0.57	0.66	0.74	35
6.19	0.52	0.59	0.66	51
7.39	0.51	0.57	0.64	54

Table 8
Variation of cost of energy (COE) (€/kWh) due to a 20% discount on the wind turbine's initial price in each location.

Wind speed (m/s)	COE		
	Diesel: 1.2 €/L	Diesel: 1.5 €/L	Diesel: 1.8 €/L
3.92	0.61	0.71	0.80
5.08	0.55	0.64	0.72
6.19	0.50	0.57	0.64
7.39	0.49	0.55	0.62

The nearest stand-alone system to the electricity grid is the most economic with the total NPC 162550€, while the NPC of the most economic hybrid system is 362550€ when the diesel price is 1.2 €/L and the location has an average speed of 7.39 m/s. The NPC of the hybrid system for all studied diesel price is higher than the NPC with only grid, except the grid to 9 km. In this case, is lower in all locations if the diesel price is 1.8 €/L.

Fig. 8 shows the variation of the COE in the studied locations according to average wind speed. We compare the option of a stand-alone system, considering different diesel prices, with a base price of 1.5 €/L and a price variation of 20%, with a grid-connected system considering different electricity prices. Electricity's base price is 0.16 €/kWh and its price variation is 20%.

In Fig. 8, there are four groups of broken lines that represent the system supplied only by the electrical grid. Within each of these groups are represented electricity prices: 0.128, 0.160 and 0.192 €/kWh. Continuous lines represent the stand alone system with different diesel prices to supply the generator in the installation.

It is observed that in all locations, if the price of diesel is 1.8 €/L, the stand-alone system would not be profitable independent of distance to the grid. Also if the distances to the network are lower than 5 km, stand-alone systems have the highest COE. Moreover if the diesel price is 1.5 €/L, the COE of stand-alone systems is lower only if the network is at more than 9 km, regardless of location. It is perhaps more remarkable that only in two locations with higher speeds, the COE of stand-alone systems is less.

These results show, according to Henry [44,45], the need for financial incentives to make certain technologies economically feasible. Implementation conditions change depending on the country and type of renewable energy. Also Ross et al. [46] detail the effect of increased RF into the drop in energy costs over caused by the size of the turbine.

Table 7 presents the values of the COE according to the three diesel prices considered and the values of the RF of the four locations studied. In Table 7, we can see that the lowest COE is in locations with a higher average wind speed and the lowest diesel price. Regarding RF, in locations with an average wind speed of 6.19 and 7.39 m/s, 51% and 54% of the energy demand is provided by wind turbine respectively.

Table 9
Variation of COE (€/kWh) according to the nominal capacity of the batteries of the hybrid system in each location studied with a diesel price of 1.5 €/L.

Wind speed (m/s)	Battery capacity			
	200 Ah	300 Ah	600 Ah	800 Ah
3.92	0.73	0.71	0.70	0.69
5.08	0.66	0.64	0.62	0.61
6.19	0.59	0.56	0.54	0.54
7.39	0.55	0.51	0.47	0.45

Himri et al. [12] show that in Algeria, a stand-alone wind-diesel hybrid system is economically viable with wind speeds of 5.48 m/s for 600 kW wind turbines without energy storage available. Moreover Shaahid [22] put emphasis on the percentage fuel savings by using hybrid wind–diesel–battery system (100-kW WECS, 175-kW diesel system, 4 h storage) is 27% as compared to diesel-only situation. When there is an increase of 25% of the initial price of the wind turbine, produces an average increase of 0.02 €/kWh in the COE with respect to the base case. Fig. 9 represents the variation.

Table 8 shows the values of the COE according to the three prices of diesel considered, if the wind turbine's price is reduced 20% due to public funding. When we compare Tables 7 and 8, we can see that the decrease in the initial price of the turbine by 20% provides a decrease of COE at 0.02 €/kWh in all cases studied. As a result, in the locations of 6.19 and 7.39 m/s average speed, stand-alone systems provide COE values lower than those obtained by the grid to 9 km away.

By increasing the capacity of the batteries, diesel consumption is lower and therefore the COE is also lower and in many of the cases studied isolated system is more competitive than the system connected to the network. Table 9 shows the variation of the COE

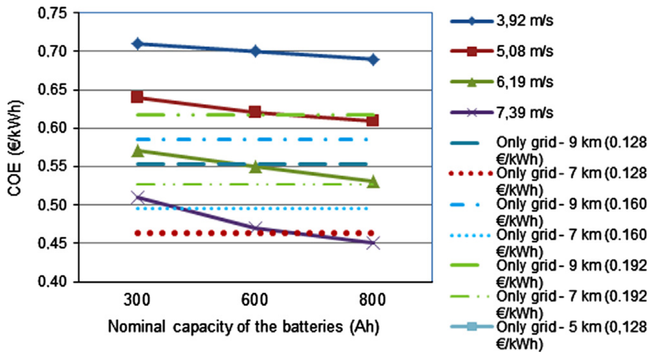

Fig. 10. Variation in the cost of energy (COE) (€/kWh) comparing the size of the battery in the stand-alone system with grid-connected systems in the studied locations.

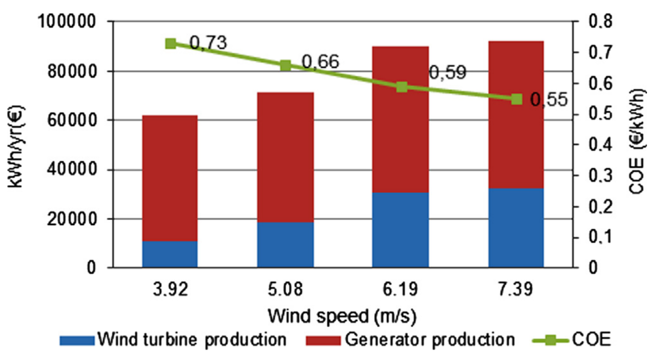

Fig. 11. Electricity supply (kWh/yr) in each location studied and its variation in cost of energy (COE) (€/kWh).

Table 10
Cost of energy (COE) (€/kWh) with a turbine's lifespan of 15 years.

Wind speed (m/s)	Diesel price		
	1.2 €/L	1.5 €/L	1.8 €/L
3.92	0.66	0.76	0.85
5.08	0.60	0.69	0.77
6.19	0.55	0.62	0.69
7.39	0.54	0.60	0.67

according to the increase in nominal capacity of the batteries analyzed in the four studied locations. If we change from a 200 Ah-battery to 800 Ah the COE will drop from 5% in the first location, with speed of 3.92 m/s, up to 18% on location with 7.39 m/s wind speed. If the battery size is 800 Ah, at the location with 7.39 m/s, stand-alone system has lower COE, regardless of the price of energy, when the distances from the grid are at least of 7 km. Also at the location 6.19 m/s average speed for this size battery, the COE is lower that obtained with the grid of more than 9 km. These results are in line with other works [22,29,46] and Fig. 10 shows these decreases.

Nandi et al. [14] studied the installation of a 7 kW wind turbine at a location with average wind speed of 5.3 m/s and electric demand of 160 kW/d. Considering an annual storage capacity of 5%, the wind–diesel hybrid system will reduce NPC as well as COE to about 20% and the diesel consumption could be reduced to about 50% of its present annual consumption.

Fig. 11 shows the annually produced electricity by the wind turbine so as diesel generator at each location. The higher the wind speed, increase the contribution of the turbine. It will reach the value of 51% in location with an average wind speed of 6.19 m/s and 54% in location with a speed of 7.39 m/s. We can also observer the decrease in COE due to increased consumption of electric energy generated by the wind turbine. When the lifespan of the turbine is 15 years instead of 25, which coincide with the duration of the project, increases the COE 0.04 €/kWh respect to the base case. The obtained results are shown in Table 10.

4. Conclusions

This article analyzes the economic option of a wind–diesel–battery system with a 20 kW turbine and an average daily consumption of 64.2–65.2 kWh/d in contrast to a system connected to the grid only. The use of wind power by means of small wind turbines can be a source of important alternative energy for rural electrification.

According to the data obtained in the simulation, the lowest values in the NPC and in the COE occur when the system is connected to the electricity grid. The stand-alone system begins to be economically competitive after distances of 9 km and depending on the average wind speed and energy prices. We can infer that in locations with an average wind speed higher than 7.39 m/s a stand-alone system is profitable as long as the distance to the electricity grid is higher than 7 km, the price of electricity is 0.192 €/kWh and diesel price is 1.8 €/L.

If there is a 25% increase from the wind turbine's initial price, it brings about an average increase of 0.02 €/kWh in the value of the COE and If lifespan of the turbine were 15 years, instead of 25 years, the cost of energy would be 0.04 €/kWh higher.

Finally if we change from a 200 Ah-battery to 800 Ah, the COE will drop 18% on the location with 7.39 m/s average wind speed. If the battery size is 800 Ah, at the location with 7.39 m/s, stand-alone system has lower COE, regardless of the price of energy, when the distances from the grid are at least of 7 km. From these situations off-grid rural electrification becomes economically attractive.

If it decreases wind turbine's initial price a 20%, the COE decreases an average of 0.02 €/kWh. The difference between the COE is most noticeable in areas with higher average wind speed, so that it would be the help that occur in these locations and thus may increase the use of small wind turbines as occurs in other countries [28].

Acknowledgments

This research was supported by the Xunta de Galicia through the INCITE Programme: 09REM001201PR.

References

[1] European Commission. 2030 climate and energy goals for a competitive, secure and low-carbon EU economy. ⟨http://ec.europa.eu/energy/2030_en.htm⟩; 2014.
[2] IEA. Energy technology perspectives. pathways to a clean energy system. International Energy Agency, Paris; 2012. p. 690. isbn:978-92-64-17488-7.
[3] REN21. Renewables 2013 global status report. Available from: ⟨http://www.ren21.net/Portals/0/documents/Resources/GSR/2013/GSR2013_lowres.pdf⟩; 2013.
[4] Lundsager P, Bindner H, Clausen NE, Frandsen S, Hansen LH, Carsten J. Isolated systems with wind power. Roskilde: Risø National Laboratory; 2001.
[5] Connolly D, Lund H, Mathiesen BV, Leahy M. A review of computer tools for analyzing the integration of renewable energy into various energy systems. Appl Energy 2010;87:059–82.
[6] Kaundinya DP, Balachandra P, Ravindranath NH. Grid-connected versus standalone energy systems for decentralized power: a review of the literature. Renew Sustainable Energy Rev 2009;13(8):2041–50. http://dx.doi.org/10.1016/j.rser.2009.02.002.
[7] Khan M, Iqbal M. Pre-feasibility study of stand-alone hybrid energy systems for applications in Newfoundland. Renew Energy 2005;30:835–54.
[8] Habib MA, Said SAM, El-Hadidy MA, Al-Zaharna I. Optimization procedure of hybrid photovoltaic wind energy system. Energy 1999;24:919–29.

[9] Kaldellis JK, Kavadias KA, Koronakis PS. Comparing wind and photovoltaic stand-alone power systems used for the electrification of remote consumers. Renew Sustainable Energy Rev 2007;11:57–77. http://dx.doi.org/10.1016/j.rser.2004.12.001.
[10] Panapakidis IP, Sarafianos DN, Alexiadis MC. Comparative analysis of different grid-independent hybrid power generation systems for a residential load. Renew Sustainable Energy Rev 2012;16:551–63. http://dx.doi.org/10.1016/j.rser.2011.08.021.
[11] Kolhe M, Kolhea S, Joshib JC. Economic viability of stand-alone solar photovoltaic system in comparison with diesel-powered system for India. Energy Econ 2002;24:155–65.
[12] Himri Y, Boudghene A, Draouic B, Himri S. Techno-economical study of hybrid power system for a remote village in Algeria. Energy 2008;33:1128–36. http://dx.doi.org/10.1016/j.energy.2008.01.016.
[13] Kamel S, Dahl C. The economics of hybrid power systems for sustainable desert agriculture in Egypt. Energy 2005;30:1271–81.
[14] Nandi SK, Ghosh HR. Techno-economical analysis of off-grid hybrid systems at Kutubdia Island, Bangladesh. Energy Policy 2010;38:976–80.
[15] Karki R, Billinton R. Reliability/cost implications of PV and wind energy utilization in small isolated power systems. IEEE Trans Energy Convers 2001;16:368–72.
[16] Hernández G, Probst O, Lastres O, Núñez A, Juantorena A, Andrade E, et al. Optimization of autonomous hybrid systems with hydrogen storage: life cycle assessment. Int J Energy Res 2012;36:749–53.
[17] Geem ZW. Size optimization for a hybrid photovoltaic–wind energy system. Electr Power Energy Syst 2012;42:448–51.
[18] Carpentiero V, Langella R, Testa A. Hybrid wind-diesel stand-alone system sizing accounting for component expected life and fuel price uncertainty. Electr Power Syst Res 2012;88:69–77.
[19] Bernal JL, Dufo R. Simulation and optimization of stand-alone hybrid renewable energy systems. Renew Sustainable Energy Rev 2009;13:2111–8.
[20] Celik AN. Optimisation and techno-economic analysis of autonomous photovoltaic–wind hybrid energy system in comparison to single photovoltaic and wind systems. Energy Convers Manag 2002;43(18):2453–68.
[21] Kaldellis JK, Kavadias KA, Filios AE. A new computational algorithm for the calculation of maximum wind energy penetration in autonomous electrical generation systems. Appl Energy 2009;86:1011–23.
[22] Shaahid SM. Impact of battery storage on economics of hybrid wind-diesel power systems in commercial applications in hot regions. Int J Energy Res 2013;37:1405–14.
[23] Dalton GJ, Lockington DA, Baldock TE. Feasibility analysis of renewable energy supply options for a grid-connected large hotel. Renew Energy 2009;34:955–64.
[24] Kaldellis JK, Zafirakis D, Kavadias K. Minimum cost solution of wind–photovoltaic based stand-alone power systems for remote consumers. Energy Policy 2012;42:105–17.
[25] Lujano-Rojas JM, Monteiro C, Dufo-López R, Bernal-Agustín JL. Optimum load management strategy for wind/diesel/battery hybrid power systems. Renew Energy 2012;44:288–95.
[26] Notton G, Muselli M, Poggi P, Louche A. Decentralized wind energy systems providing small electrical loads in remote areas. Int J Energy Res 2001;5:141–64.
[27] Elhadidy MA, Shaahid SM. Parametric study of hybrid (wind+solar+diesel) power generating systems. Renew Energy 2000;21:129–39.
[28] Thompson S, Duggirala B. The feasibility of renewable energies at an off-grid community in Canada. Renew Sustainable Energy Rev 2009;13:2740–5.
[29] Weis TM, Ilinca A. The utility of energy storage to improve the economics of wind–diesel power plants in Canada. Renew Energy 2008;33:1544–57. http://dx.doi.org/10.1016/j.renene.2007.07.018.
[30] Giannoulis ED, Haralambopoulos DA. Distributed Generation in an isolated grid: methodology of case study for Lesvos – Greece. Appl Energy 2011;88(7):2530–40.
[31] HOMER 2. v2.81, February 8, 2012. Copyright© Homer Energy, LLC.
[32] Blanco MI. The economics of wind energy. Renew Sustainable Energy Rev 2009;13:1372–82.
[33] Irimia S, Escudero C, Álvarez C. La eficiencia energética en las explotaciones de vacuno lechero en Galicia (España). In: Proceedings of the 16th Congreso internacional de ingeniería de proyectos, Valencia (Spain), July 11–13; 2012. p. 1235–46.
[34] IDAE. Auditorías energéticas en instalaciones ganaderas. Parte 1: Manual para la realización de auditorías energéticas en instalaciones ganaderas. Serie: Ahorro y Eficiencia Energética en la Agricultura. Instituto para la Diversificación y Ahorro de la Energía, Madrid; 2010. p 83.
[35] Bartolomé DJ, Posado R, Bodas R, Tabernero de Paz MJ, García JJ, Olmedo S. Dairy cattle farm electricity consumption in Castilla y León. Arch Zootec 2013;62(239):447–55.
[36] Capareda SC, Mukhtar S, Engler C, Goodrich LB. Energy usage survey of dairies in the Southwestern United States. Appl Eng Agric 2010;26(4):667–75.
[37] Kraatz S, Berg WE. Energy demand for milking dairy cows. ASABE paper No. 074175. St. Joseph, Michigan; 2007.
[38] Nyserda. Dairy farm energy audit summary. New York State Energy Research and Development Authority, 2003.
[39] Ministerio de Industria y Energía. Resolución de 24 de septiembre de 2013, de la Dirección General de Política Energética y Minas. Coste de producción de energía eléctrica y tarifas de último recurso. Boletín Oficial del Estado; 2013.
[40] Proyecto tipo líneas de baja tensión aéreas. Eon distribución. Ministerio de Industria, Energía y Turismo. Legislación Nacional – REBT – Especificaciones Particulares de las Empresas Suministradoras; 2013. 〈http://www.f2i2.net/legislacionseguridadindustrial/〉.
[41] 〈http://www.ingeteam.com/〉.
[42] 〈http://www.hoppecke.es/〉.
[43] 〈http://www.taiguergeneradores.com/〉.
[44] McHenry MP. Small-scale (6 kWe) stand-alone and grid-connected photovoltaic, wind, hydroelectric, biodiesel, and wood gasification system's simulated technical, economic, and mitigation analyses for rural regions in Western Australia. Renew Energy 2012;38:195–205.
[45] McHenry MP. A technical, economic, and greenhouse gas emission analysis of a homestead-scale grid-connected and stand-alone photovoltaic and diesel systems, against electricity network extension. Renew Energy 2012;38:126–35.
[46] Ross M, Abbey C, Jo´os G. Cost analysis for sizing energy storage systems in wind-diesel microgrids. In: Proceedings of the general meeting of the IEEE-power-and-energy-society (PES) detroit, MI, July 24–28; 2011.